INTERNATIONAL CONFERENCE
ON
EXPERIMENTAL FLUID MECHANICS

June 17～21, 1991 CHENGDU, CHINA

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CHINESE AERODYNAMICS RESEARCH SOCIETY

CHARACTERISATION OF ROTATING STALL IN A CENTRIFUGAL IMPELLER

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ABSTRACT

Detailed measurements through hot-wire anemometry at the outlet of a centrifugal impeller revealed a rotating stall at a flow coefficient of 0.057. As the flow coefficient is reduced to 0.034, the behaviour of the rotating stall pattern changes. An experimental method is described to estimate the stall propagating speed and the number of stall cells. These two parameters characterise the rotating stall in a centrifugal impeller.

NOMENCLATURE

b	axial distance (m)
d	diameter (m)
f	frequency (Hz)
m	mass flow rate (kg/sec.)
T	time (ms)
U	peripheral speed (cycles/sec.)
ρ	density of the fluid (kg/m3)
ϕ	flow coefficient = $4m/(\rho_o d_2^2 U_2)$
θ	angle in the circumferential direction

SUBSCRIPTS

o	inlet duct
1	impeller inlet
2	impeller outlet
p	probe
s	stall

INTRODUCTION

Flow instabilities such as rotating stall and surge are not only important because of their influence on efficiency and mass flow range but also because they contribute to vibrational excitation resulting in mechanical failures. Braembussche, et. al (1) used hot-wire anemometers at impeller outlet to investigate the flow instabilities. One hot-wire anemometer is placed at rotor inlet, two at diffuser inlet at 90 deg. apart on the circumference. The stall cell was characterised in terms of its frequency and number of cells. Similar investigations were carried out by Kubo and Murata (2) to measure the rotating stall at impeller outlet.

Kinoshita and Senoo (3) experimentally determined the of rotating stall for three very small specific speed centrifug blowers. Through experiments it was demonstrated that the blowers did not stall until the flow coefficient was reduced to very small values. A theoretical model for rotating stall in the vaneless diffuser of a centrifugal compressor was presented by Frigne and Braembussche (4). It was shown that, depending on the diffuser geometry and the diffuser inlet flow angle, a transient perturbation of the outlet static pressure will generate a rotating flow pattern, if the periodicity of this perturbation corresponds to the experimentally observed number of cells. Otugen and Hwang (5) investigated the rotating stall phenomenon and its relation to diffuser geometry in a model vaneless diffuser rig. It was shown that critical mass flow rate for the onset of rotating stall depends on diffuser width and diffuser radius ratio. Critical mass flow rate for the onset of stall decreases with decreasing diffuser width. Larger radius ratio results in smaller critical mass flow rate. The flow at the stall line of a centrifugal compressor with vaneless diffuser was investigated at different speeds by Kammer and Rautenberg (6). The two different types of periodic stall appeared at higher speeds were verified from comparison of signals from peripherally spaced pressure transducers. From a detailed investigation of high frequency rotating stall, it was shown that the rotating stall was generated in the impeller by a periodic breakdown of energy transfer from the rotor to the flow.

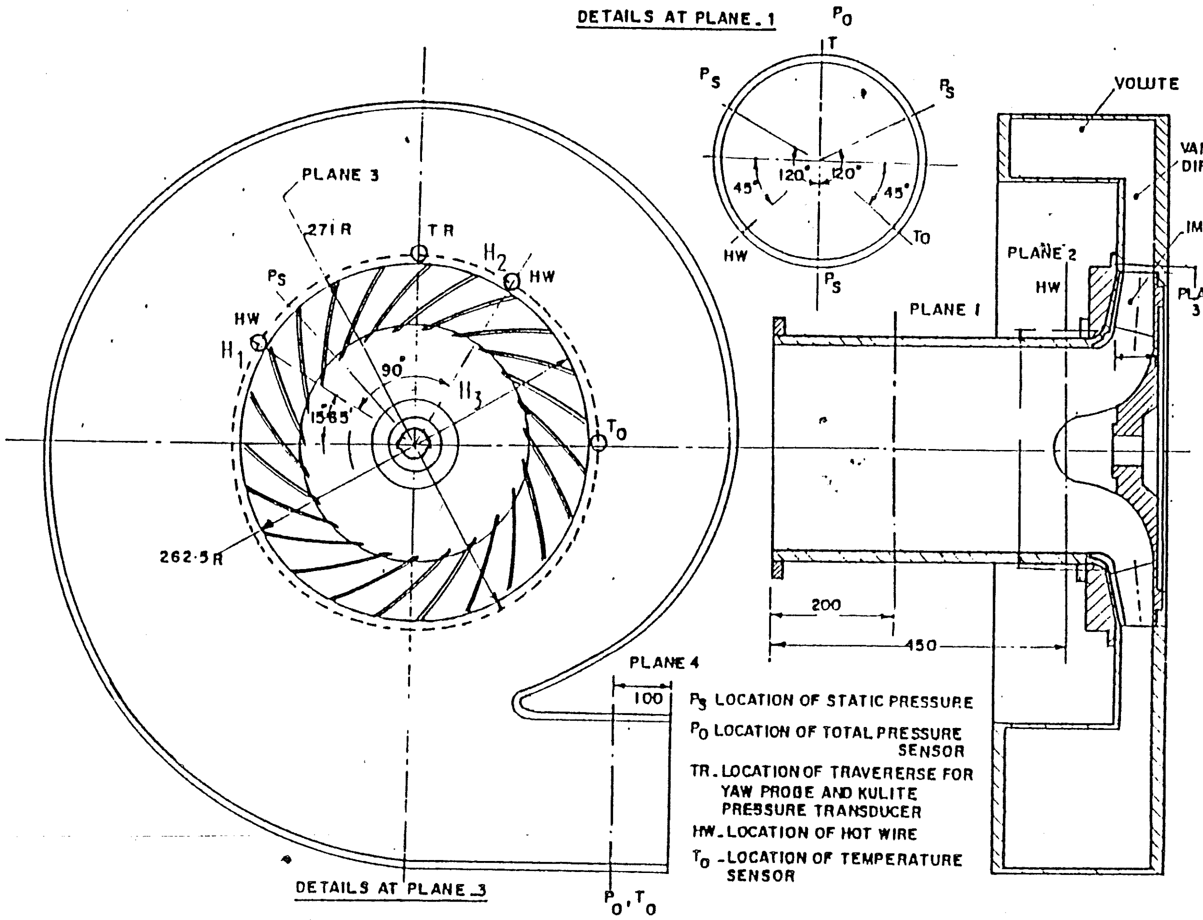


Fig. 1 Location of measurement planes

EXPERIMENTAL SET-UP

A centrifugal impeller of 525 mm diameter 45.5 mm width with 23 vanes backswept by 40 degrees with reference to radial direction was rotated by a D.C. motor. Thyristor control with feed back for the D.C. motor ensured maintenance of the speed to an accuracy of 0.1%. An electronic torquemeter coupled in between the gear box and the compressor was used to measure the speed and input power. A bell mouth in the inlet duct was used to ensure uniform flow to the compressor. A throttle plate at the exit of the volute casing was used to vary the mass flow rate through the impeller.

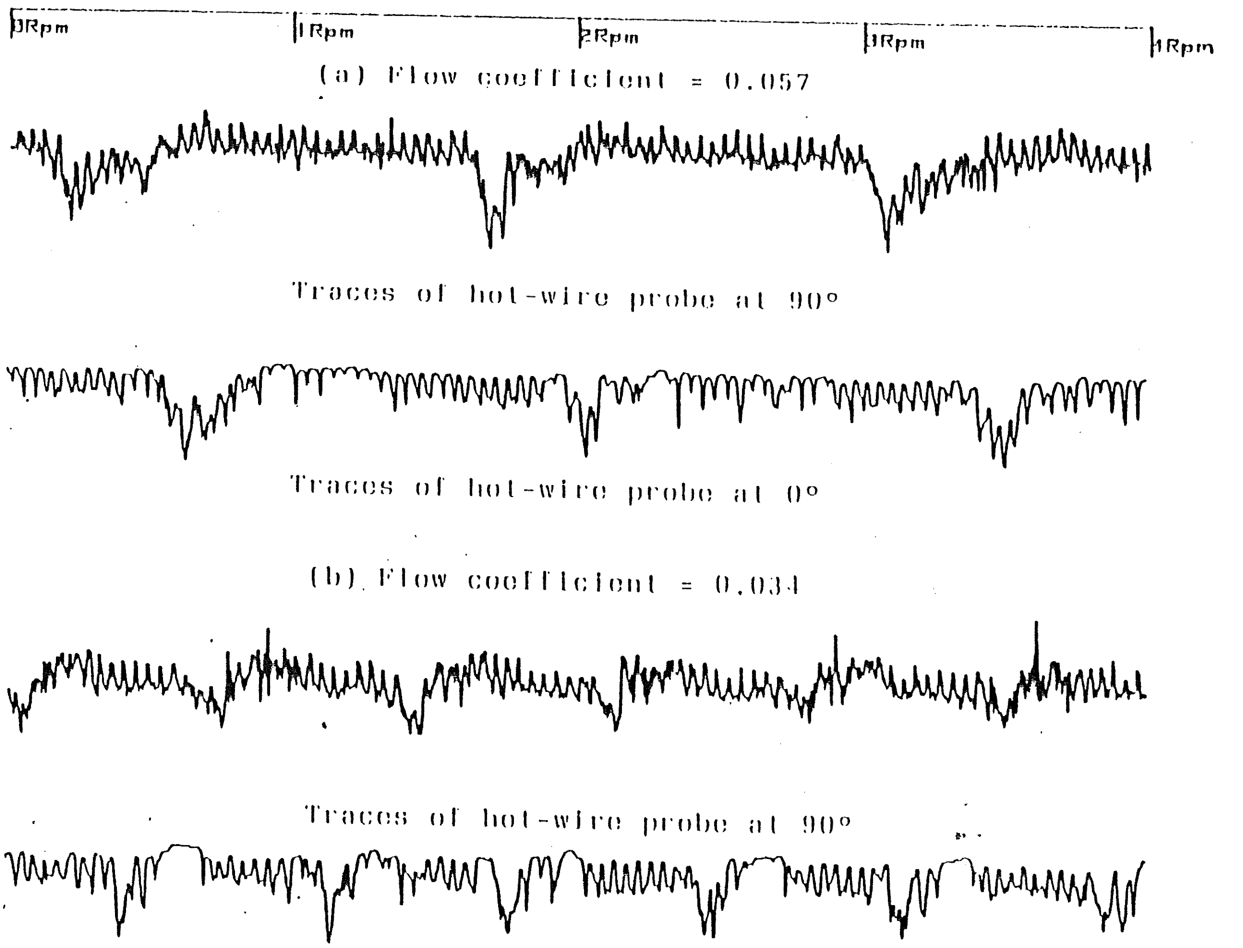


Fig. 2 Instantaneous hot-wire anemometry signals taken at impeller outlet for two different flow coefficients, with angular displacement of 90° between two hot-wire probes.

INSTRUMENTATION

Two hot-wire anemometers were placed 8 mm radially outwards from the impeller tip and mid way between hub and shroud side walls. These two anemometers were displaced circumferentially by 90 degrees apart (H_1 and H_2 in Fig. 1). The hot-wire anemometers were oriented approximately in the average flow direction. One more hot-wire anemometer (H_3 in Fig. 1) was placed at impeller inlet to study the propagation of rotating stall upstream of the impeller. The instantaneous hot-wire signals were captured

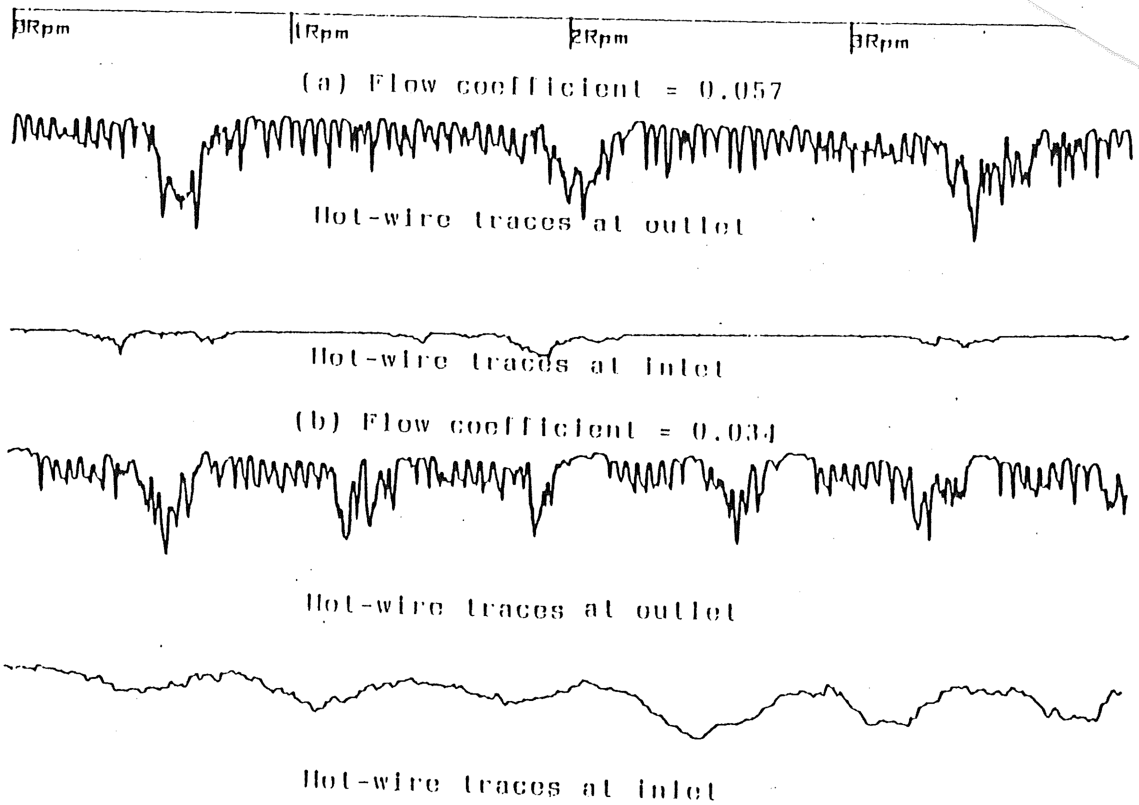
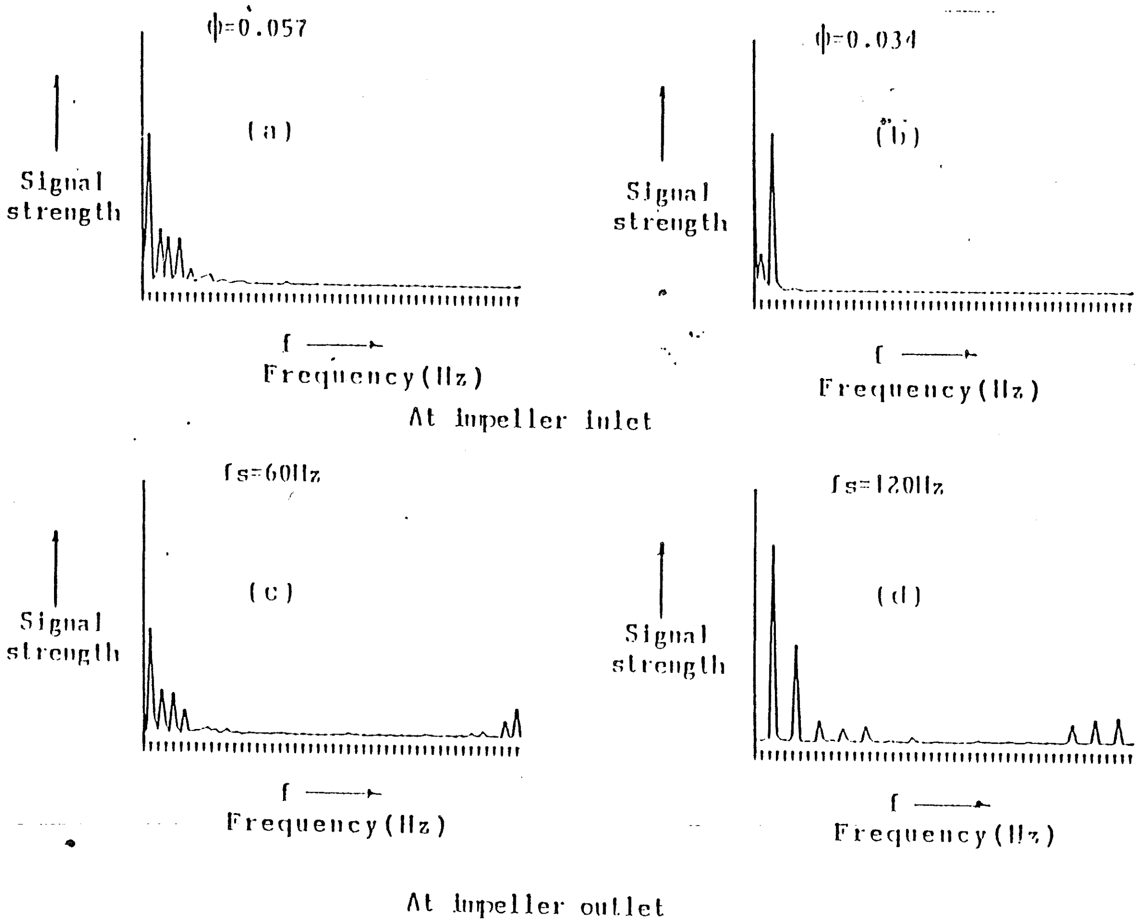


Fig.3 Instantaneous hot-wire anemometry signals taken at impeller inlet and outlet for two different flow coefficients.



NOTE: Each division on X-axis is 40Hz.

Fig. 4 Auto power spectrum of hotwire signal at stalled condition through a computer controlled dual beam signal analyser and recorded through its memory on to magnetic disks. An once per revolution pulse generated from a magnetic pick up and shaft projection was used to trigger simultaneously both the hot-wire signals. All the hot-wire signals triggered simultaneously by the magnetic pick-up were recorded for a duration of 50 milli seconds which correspond to nearly 4 revolutions of the rotor. From the recorded signals of the two sensors at outlet the speed of propagation of the stall cell and number of stall cells could be estimated.

RESULTS AND DISCUSSIONS

Figs. 2a and 2b shows the hot-wire signals obtained at impeller outlet just after stall for a flow coefficient of 0.057. A large dip in the hot-wire signals (Fig. 2a) indicate rotating stall cell. As the flow coefficient is reduced to a lower value, 0.034, the number of dips in the hot-wire signals increases (Fig. 2b), indicating the change in behaviour of the stall. To study the behaviour of the inlet flow in the stalled condition the signals of the hot-wire sensors placed one very close to the impeller inlet and the other at impeller outlet were simultaneously recorded at both flow coefficients. These signals are shown in Figs. 3a and 3b. It is observed from these figures that there is a dip in the signal of the inlet hot-wire (Fig. 3a) corresponding to every dip in the signal of the outlet hot-wire probe (Fig. 2a), indicating the stall cell has propagated upstream. The intensity of the stall depends on the flow coefficient. As the flow coefficient is reduced, the rotating stall pushes the flow towards surge.

The recorded hot-wire signals at impeller inlet and outlet were analysed through a signal analyser. The Fourier transformation of these signals are shown in Figs. 4a to 4d. It is observed that the frequency of the stall cells at impeller inlet and outlet coincided with 60 Hz. at higher flow coefficient (Figs. 4a and 4c) and 120 Hz. at lower flow coefficient (Figs. 4b and 4d). By calculating the time interval between the dip of one hot-wire anemometer signal to the dip of the other hot-wire anemometer signal (both at outlet displaced by 90 degrees), the speed of the stall cell can be calculated.

Consider the hot-wire signals obtained at flow coefficient of 0.057. The interval between the dip of the signal in the first hot-wire sensor to the dip of the signal in the second hot-wire sensor is about 20*12/57 ms. This corresponds to 90 degrees, which is the angular displacement of the two sensors at impeller outlet. One revolution of the impeller corresponds to 12 ms on the hot-wire signal.

Hence to travel 90 deg. the stall cell takes

$$\Delta T = 20*12/57 = 4.21 \text{ ms}$$

To travel 360 deg. (1 revolution) stall cell takes 16.84 ms

Absolute speed of stall U_s = 1000/16.84 cycles/sec.

= 60 cycles/sec.

Rotor speed = 1000/12 = 83 cycles/sec.

Relative speed of stall cell = 60 - 83 = -23 cycles/sec.

Ratio of stall speed to impeller speed = 23/83

= 1/4 (approx.)

The frequency of the stall cell is given by $f_s = N_s / U_s$ (1)

Where, N_s is the number of number of stall cells, U_s is the speed of the stall cell and f_s is the frequency of the stall cell, which is obtained from frequency spectrum.

From the above equation we get at flow coefficient, ϕ =0.057, N_s=1 cell as f_s=60 cycles/sec. and at flow coefficient. ϕ =0.034, N_s=2 cells as f_s =120 cycles/sec.

To find out the extent of stall cell the hot-wire anemometer was traversed along the impeller width from hub side wall to shroud side wall. At nine locations along the impeller width the hot-wire signals

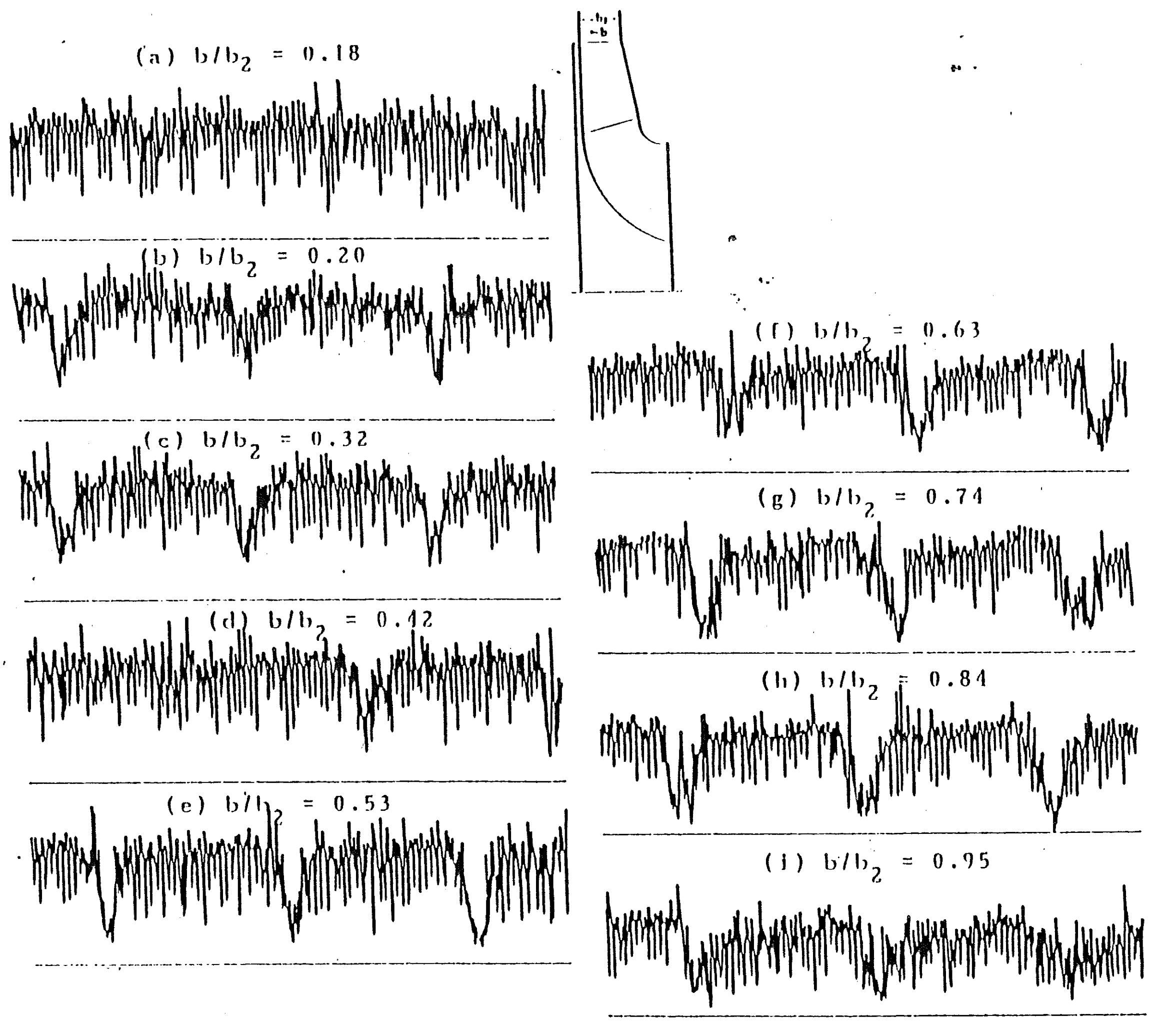


Fig.5 Instantaneous hot-wire traces at impeller outlet for flow coefficient = 0.057.

were recorded. These are shown in Fig. 5. The recorded signals showed that the rotating stall exists at all locations indicating a full span stall.

CONCLUSIONS

At initiation of stall the impeller goes into rotating stall with a single cell covering about seven blade passages rotating at one-fourth of impeller speed opposite to direction of rotation in the relative frame of reference. Well inside the stall regime at lower flow coefficient, there are two rotating stall cells each covering approximately about three blade passages with the cells being opposite to each other, i.e., displaced by 180 deg. The stall cells again rotate at one-fourth of impeller speed opposite to the direction of impeller rotation in relative frame of reference.

ACKNOWLEDGEMENTS

The authors thank Mr.R.Rajendran of Propulsion Division, National Aeronautical Laboratory, Bangalore, India for the technical assistance given for carrying out the experiments.

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